

# The nature of the infrared counterpart of IGR J19140+0951

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## ABSTRACT

The INTEGRAL observatory has been (re-)discovering new X-ray sources since the beginning of nominal operations in early 2003. These sources include X-ray binaries, Active Galactic Nuclei, cataclysmic variables, etc. Amongst the X-ray binaries, the true nature of many of these sources has remained largely elusive, though they seem to make up a population of highly absorbed high-mass X-ray binaries. One of these new sources, IGR J19140+0951, was serendipitously discovered on 2003 Mar 6 during an observation of the galactic microquasar GRS 1915+105. We observed IGR J19140+0951 with UKIRT in order to identify the infrared counterpart. Here we present the H- and K-band spectra. We determined that the companion is a B0.5-type bright supergiant in a wind-fed system, at a distance  $\lesssim 5$  kpc.

**Key words:** X-rays: binaries – stars: individual: IGR J19140+0951 – infrared: stars

## 1 INTRODUCTION

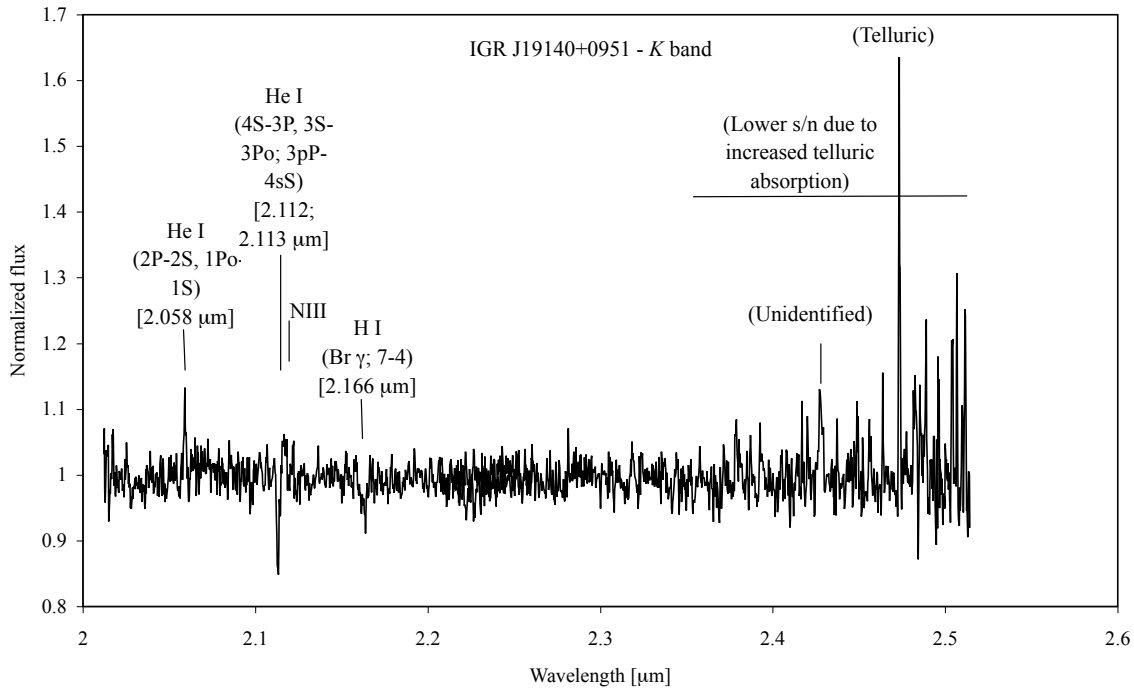
The INTERnational Gamma-Ray Astrophysics Laboratory (*INTEGRAL*, Winkler et al. 2003), launched on 2002 October 17 and beginning normal operations in early 2003, has been discovering (or in some cases re-discovering) many new X-ray and gamma-ray sources. The first such source, discovered with the IBIS/ISGRI instrument (Lebrun et al. 2003; Ubertini et al. 2003) during a galactic plane scan, was designated IGR J16318–4848 (Walter et al. 2003). The infrared/optical counterpart indicates that IGR J16318–4848 is probably a high-mass X-ray binary. Furthermore, the source is observed to be intrinsically strongly absorbed by cold matter. Subsequently, more than two hundred new sources have been discovered to date (e.g. Bodaghee et al. 2007; Bird et al. 2007), the majority being low-mass or high-mass X-ray binaries, and Active Galactic Nuclei. Amongst the high-mass X-ray binaries, a large fraction of the sources are found to be heavily obscured sources, exhibiting much larger column densities than would be expected along the line of sight (e.g. Kuulkers 2005). These systems are likely to be supergiant high-mass X-ray binaries, largely missed in previous X-ray surveys which scanned the skies with instruments geared more towards the softer X-ray energies.

One of the new sources discovered with *INTEGRAL* is IGR J19140+0951 (Hannikainen, Rodriguez & Pottschmidt 2003; Hannikainen et al. 2004). Inspection of the high energy archives showed it to be the most likely hard X-ray counterpart to the poorly studied *EXOSAT* source EXO 1912+097 (Lu et al. 1996). A target of opportunity was performed on IGR J19140+0951 with the *Rossi X-Ray Timing Explorer (RXTE)* – preliminary analysis showed the source had a rather hard spectrum, fitted with a power law of photon index 1.6 and an absorption column density  $N_H = 6 \times 10^{22} \text{ cm}^{-2}$  (Swank & Markwardt 2003). Timing analysis of the *RXTE*/ASM data revealed an X-ray period of 13.55 days (Corbet, Hannikainen & Remillard 2004). This implies that the source was detected even in the early days of the *RXTE* mission, which in turn suggests that IGR J19140+0951 is a persistent source although most of the time in the faint state.

High energy spectral analysis of IGR J19140+0951 covering the period of its discovery (i.e. *INTEGRAL* revolution 48) was presented in Hannikainen et al. (2004). During this observation, the source, although very variable, showed two distinct spectral behaviours. The first one manifests a thermal component (blackbody-like) in the soft X-ray and a hard X-ray tail, while the second one is harder and can be interpreted as originating from thermal Comptonization.

In a follow-up paper, we reported on high energy ob-

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**Figure 1.** Normalized short- and long-K spectra of the infrared counterpart of IGR J19140+0951. Spectroscopic features constraining the spectral type are indicated. The CO bandheads characteristic of late-type stars are clearly absent (e.g. at 2.2935, 2.3227, 2.3535  $\mu\text{m}$ ). Strong emission features longward of 2.35  $\mu\text{m}$  are due to imperfect cancellation of telluric bands with the standard.

servations performed with *RXTE* on three separate occasions: in 2002, 2003 and again in 2004 (Rodríguez et al. 2005). We also analyzed *INTEGRAL* observations from the period early March to mid-May 2003. We showed that IGR J19140+0951 spends most of its time in a very low-luminosity state characterized by thermal Comptonization. On some occasions, we observed the luminosity to vary by a factor of 10 during which the spectrum can show evidence of a thermal component, besides thermal Comptonization by a hotter plasma than during the low luminosity state. The spectral parameters derived strongly pointed to IGR J19140+0951 hosting a neutron star, although a black hole could not be ruled out, and we concluded that IGR J19140+0951 is most probably a High Mass X-ray Binary (HMXB).

*Swift* observations of the source caught it at its lowest luminosity level thus far: about five times fainter than the dimmest observation published in Rodríguez et al. (2005) and about 150 times fainter than the brightest state of the source seen with *INTEGRAL* (Rodríguez et al. 2006).

The infrared counterpart to IGR J19140+0951 was identified by in’t Zand et al. (2006), following an accurate position determination using *Chandra*, with the heavily reddened 2MASS 19140422+0952577 in the 2MASS catalogue. Recently, Nespoli, Fabregat & Mennickent (2007), based on K-band observations, estimate the spectral type of the infrared counterpart to be B1 I.

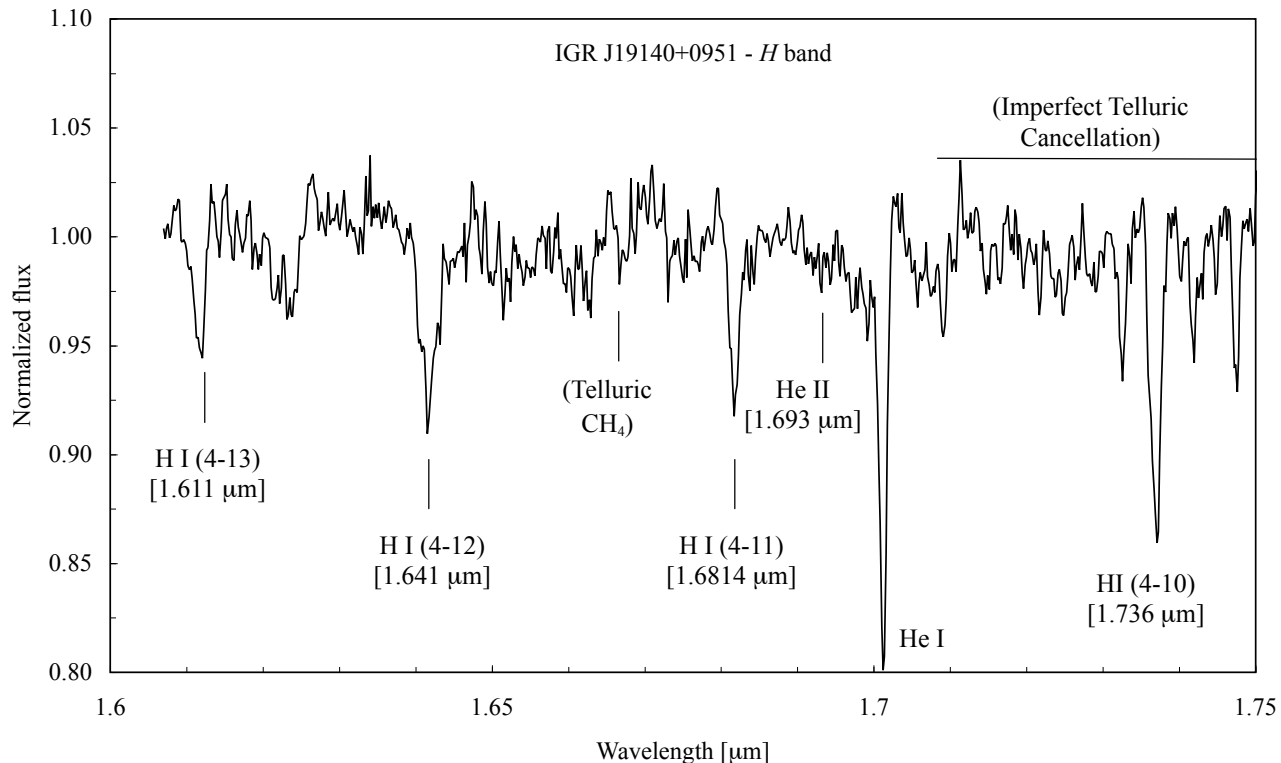
In this paper, we present both H- and K-band infrared data obtained with the UK Infrared Telescope (UKIRT) in Hawaii of IGR J19140+0951. In Section 2 we describe the observations and the data reduction, while in Section 3 we discuss the outcome of the observations.

## 2 INFRARED OBSERVATIONS

### 2.1 K-band

Near-infrared observations were carried out on the night of 2006 March 7 (UT) using UIST on the 3.8-m UKIRT at the Mauna Kea Observatory in Hawaii. The full 1024×1024-pixel array was used in conjunction with the short- and long-K grisms. A 4-pixel slit at a position angle of 12.3 degrees East of North was used in order to enable simultaneous spectroscopy of both the IGR J19140+0951 infrared counterpart and the nearby brighter star for comparison. A standard 12” nod along the slit was used. This configuration produced a total overall effective wavelength range of 2.0–2.5  $\mu\text{m}$ . The weather was clear, with seeing averaging around 0.4”. Suitable flat field frames were taken, and the data were flat fielded by the data reduction pipeline during the observations. Spectra of the F6V standard BS 7354 were taken at matching airmasses to facilitate flux calibration and cancellation of telluric absorption.

Data were reduced using the Starlink packages Figaro, Kappa and Gaia. One-dimensional spectra were extracted from the coadded sky-subtracted frames and wavelength calibrated against argon lamp spectra. Br $\gamma$  absorption was interpolated out of the standard star spectrum. This was done in order to avoid introducing contamination into the target spectra when dividing by the standard to remove telluric effects. Where necessary, cosmic ray spikes in the resultant spectra were interpolated out, and the data were linearly rebinned and flux calibrated against the known properties of the standard. The fully reduced spectra were then divided by fitted polynomial continua in order to produce the normalised spectrum shown in Fig. 1. The polynomials are established interactively using the Starlink Figaro CFIT rou-



**Figure 2.** Normalized H-band spectra of the infrared counterpart of IGR J19140+0951.

time, and typically  $\sim 20$  points are used to constrain the fit for spectra of this type. The selection of the continuum positions used is performed with reference to published stellar and telluric line lists to minimize contamination. If not simply an artifact of imperfect telluric cancellation, the feature at  $2.42\text{--}2.43\text{ }\mu\text{m}$  remains unidentified. It unfortunately falls between the wavelength ranges covered by infrared atlases, including Hanson et al. (2005). However, the possible presence of this feature does not affect the classification of the star.

## 2.2 H-band

H-band spectroscopy data were acquired on 2006 October 5 (UT) using the UKIRT/UIST long-H grism with a 4-pixel slit in second order. The same pointing, nod and slit orientation were used as for the K-band data. The total on-source integration time was 240s. One-dimensional spectra were extracted from the flat-fielded, coadded frames using the same method and data reduction software as for the K-band data, and wavelength-calibrated against an argon lamp spectrum. Although a standard star spectrum was obtained just after that of the science target, this was later found to be of insufficient quality, and so long-H observations of HD 122563 (F8IV) taken on 2005 January 30 (UT) were used instead. Extraneous photospheric lines were identified and interpolated out of the normalised standard spectrum.

Before dividing the normalised spectrum of IGR J19140+0951 with that of the replacement standard, a correction for airmass difference was also necessary. Telluric absorption features in the standard were therefore logarithmically rescaled to produce optimal cancellation in the spectrum of IGR J19140+0951 (see Sec. 3.1 of Rawlings et al.

2003 for a full description of this technique). To test the possible impact of the telluric cancellation method on key lines, the logarithmic scaling factor was varied to produce over- and under-cancellation. It was found that the equivalent width ratios of the photospheric lines used for classification by Hanson et al. (2005) varied by no more than 2 per cent. The effect of the airmass correction on the classification of the IR counterpart of IGR J19140+0951 was therefore deemed negligible.

## 3 RESULTS

In this section we summarize the results based on the K- and H-band spectra.

### 3.1 K-band spectrum

Figure 1 shows the UKIRT short- and long-K spectrum of IGR J19140+0951 (or strictly speaking, of 2MASS 19140422+0952577, the star associated with the X-ray position of IGR J19140+0951). In order to identify the stellar type of the companion to IGR J19140+0951, we used the infrared atlases of Hanson et al. (2005) and Hanson, Conti & Rieke (1996). The spectral lines we used in the identification were the He I lines at  $2.0581$  and  $2.1126\text{ }\mu\text{m}$ , the N III line at  $2.1155\text{ }\mu\text{m}$ , and the H I (Br- $\gamma$ ) line at  $2.1661\text{ }\mu\text{m}$  which are all marked in Fig. 1. The first thing to note is that the first He I line and N III are in emission, while the second He I line and H I are in absorption, which is what is expected for a hot and luminous early-B supergiant. These are the same spectral features that were used by Nespoli et al. (2007) in their classification. The fact that the He I line at  $2.0581\text{ }\mu\text{m}$

is in emission is probably a luminosity effect (Hanson et al. 1996). The relative strengths of the He I and H I point to a B0.5 or B1 star. Also, the H I line appears to be a blend of He I at  $2.161 \mu\text{m}$  and the H I itself. In addition, the N III line in emission is most prominent in the supergiant classes, i.e. luminosity class Ia or Iab. Hanson et al. (2005) mention that the N III line could also be C III.

We would like to point out that, similarly to Hanson et al. (1996), we did not use equivalent widths in our classification, as there are substantial variations between stars – we have not conducted an absolute classification but a comparison between spectra.

### 3.2 H-band spectrum

Figure 2 shows the H-band spectrum of IGR J19140+0951. The lines used in identifying the source are marked in the figure, the most prominent line being the He I line at  $1.7002 \mu\text{m}$  in absorption. Based on the narrowness of the lines, especially of the He I line, we can confirm that the source is indeed a supergiant. A study of the profile of the He I line near  $1.7 \mu\text{m}$  suggests the wings are possibly real, rather than merely a cancellation artifact. We speculate that this may indeed be due to the stellar wind. By comparing the relative strengths of the He I and H I lines in our spectrum with those of Hanson et al. (2005), we narrow down our classification and say that we are dealing with a B0.5 star. So we conclude that the companion to IGR J19140+0951 is a bright supergiant in the B0.5 class.

### 3.3 IGR J19140+0951 as an HMXB

A B0.5 supergiant counterpart identifies IGR J19140+0951 as an HMXB. Most HMXB's belong to the class of Be-binaries (Liu et al. 2000) – as we do not see the H I (Br- $\gamma$ ) line in emission, we can say that IGR J19140+0951 does not belong to this class, but instead belongs to the relatively underpopulated class of normal early B-type binaries. Indeed, of all the known HMXB's, only 25% belong to the class of supergiants (Charles & Coe 2006). The only two known HMXB's with a B0.5 star are SMC X-1 and Vela X-1, and both of these are subluminous supergiants (Liu et al. 2000). They also both contain pulsars. Other pulsars are in binary systems with either normal giants or even main sequence stars. No X-ray pulsations have been detected from IGR J19140+0951.

A B0 supergiant has a mass of  $25 M_{\odot}$  and a radius of  $30 R_{\odot}$  (Cox 2000, Table 15.8). Assuming a period of 13.55 days and a neutron star of mass  $1.4 M_{\odot}$ , the orbital separation is  $a=71.15 R_{\odot}$  and the B supergiant's Roche lobe is about  $44 R_{\odot}$ . Hence, the star is inside the Roche lobe and the system is wind-fed as presumed. If one replaces the neutron star with a 10 solar mass black hole, the Roche lobe radius of the B supergiant is then  $35 R_{\odot}$  and then the system would still remain purely wind-fed.

So far, of the  $\sim 200$  new sources discovered with *INTEGRAL* (those designated with “IGR”) 50% are as yet unclassified. Six sources, or 3%, are LMXB's, while another 32 sources are HMXB's (Bodaghee 2007). Of these HMXB's, the majority belong to the class of heavily obscured sources (e.g. Kuulkers 2005) with OB supergiant companions. The

absorption column to IGR J19140+0951 varied between  $5 \times 10^{22} - 1 \times 10^{23} \text{ cm}^{-2}$  (Rodriguez et al. 2005) making it one of the heavily obscured sources, if one takes  $2 \times 10^{22} \text{ cm}^{-2}$  to be the galactic column density. Most of the obscured sources can be found in the Norma arm of the Milky Way, whereas IGR J19140+0951 lies in the direction of the tangent to the Sagittarius arm. The abundance of heavily obscured sources in the Norma arm may be the result of it being the site with the highest formation rate of OB stars (e.g. Bronfman et al. 1996). When coupled with a compact object to form an X-ray binary, these supergiant systems are wind-fed accretors, and therefore are likely to be heavily obscured. In contrast, the Sagittarius arm has a lower OB star formation rate, and hence will contain fewer of these absorbed sources. In fact, the Norma arm is closer to the Galactic Centre than the Sagittarius arm, and its proximity to the 3-kpc molecular ring makes it a region that is naturally more dense with material favouring an enhanced birth rate of OB stars. As mentioned in Zand et al. (2006), if the association of IGR J19140+0951 with the Sagittarius arm is true, then the distance is of the order 2–6 kpc, and the implied 1–20 keV *Chandra* luminosity is then  $10^{35} \text{ erg s}^{-1}$  which is common for HMXB's. In fact, for a typical B0 supergiant the absolute K-magnitude is  $M_K=-5.8$  (Cox 2000, Tables 7.8 and 15.7) and for IGR J19140+0951 the K extinction  $A_K$  is about 1 magnitude (Cox 2000, Table 21.6) assuming  $A_V=11$  as found in Zand et al. (2006). They also measured the apparent K-magnitude to be  $m_K=8.7$ . From these numbers it follows ( $M=m+5-5 \log d - A$ , distance  $d$  in pc) that the distance is 5 kpc. Using B0 I instead of B0.5 I would give a slightly smaller distance. This supports placing the source in the Sagittarius arm.

## 4 CONCLUSIONS

We have identified the counterpart to IGR J19140+0951 as being a B0-B1 supergiant, with the most favoured type being a bright B0.5 supergiant, consistent with the estimate of Nespoli et al. (2007). This implies that IGR J19140+0951 belongs to the class of HMXB's. In addition, the absorbing column to IGR J19140+0951 suggests that it also belongs to the class of newly discovered heavily obscured *INTEGRAL* sources. We estimated a distance of  $\lesssim 5 \text{ kpc}$ , placing it in the Sagittarius arm.

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